

Next Generation Proton Decay

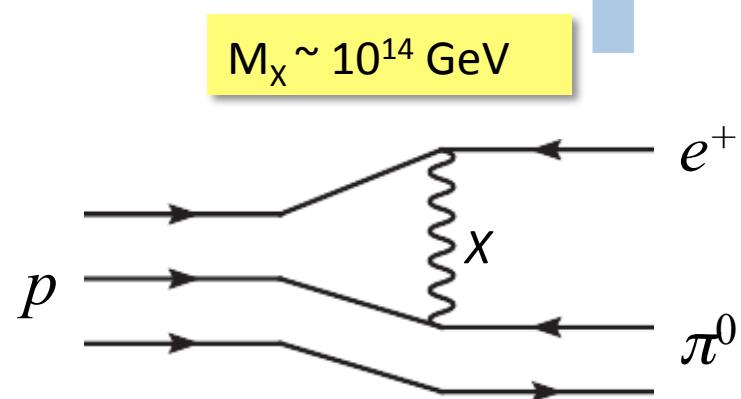
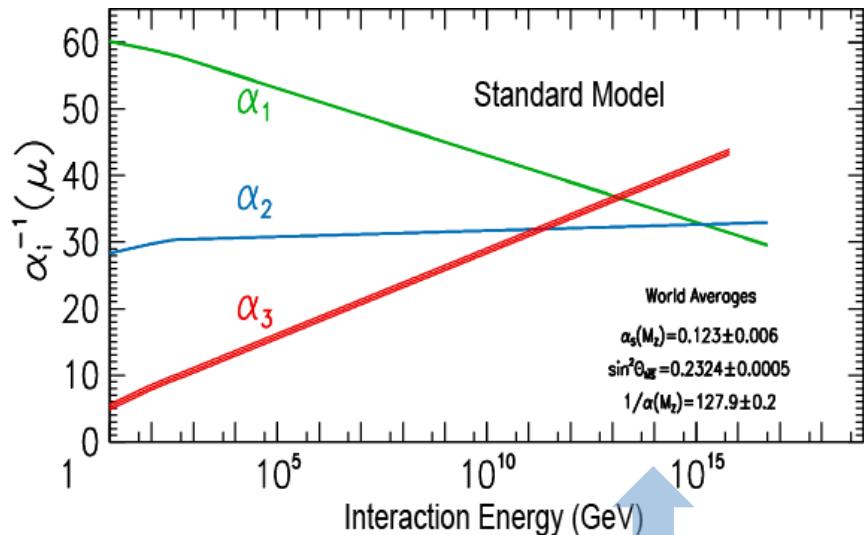
The “standard” story of
 $e^+\pi^0$ versus $K^+\nu$:
theory and experiment,
water Cherenkov and liquid argon

Ed Kearns ◆ Boston University
DUSEL planning meeting at Fermilab
August 14, 2008

Physics Case for Proton Decay

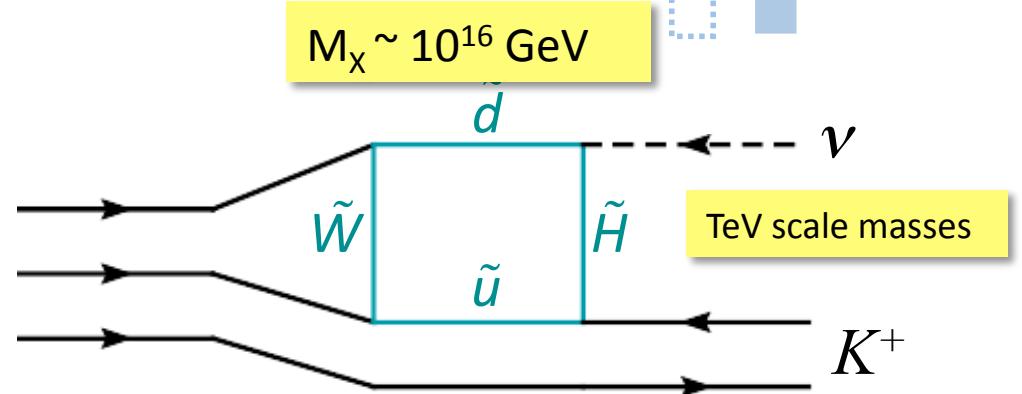
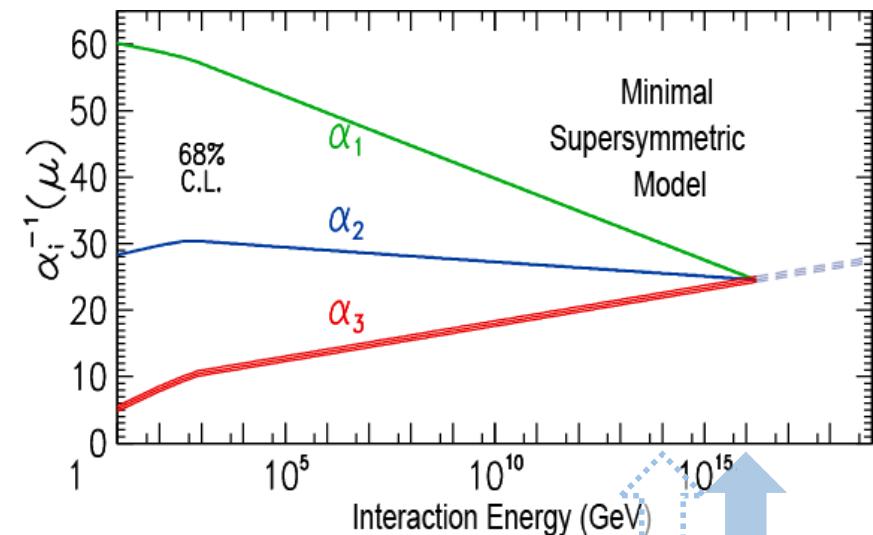
- ❖ Tests a fundamental, but unexplained symmetry: baryon number conservation.
- ❖ Grand Unified Theories make specific predictions: modes, lifetimes, branching ratios.
- ❖ Probes scales forever inaccessible to accelerators.
- ❖ May probe TeV-scale physics as well.
- ❖ Connections with cosmology: inflation, baryon asymmetry of the universe
- ❖ **New force of nature!**

Unification of Running Coupling Constants



$$\tau/B = 4.5 \times 10^{29 \pm 1.7} \text{ years } \text{SU}(5)$$

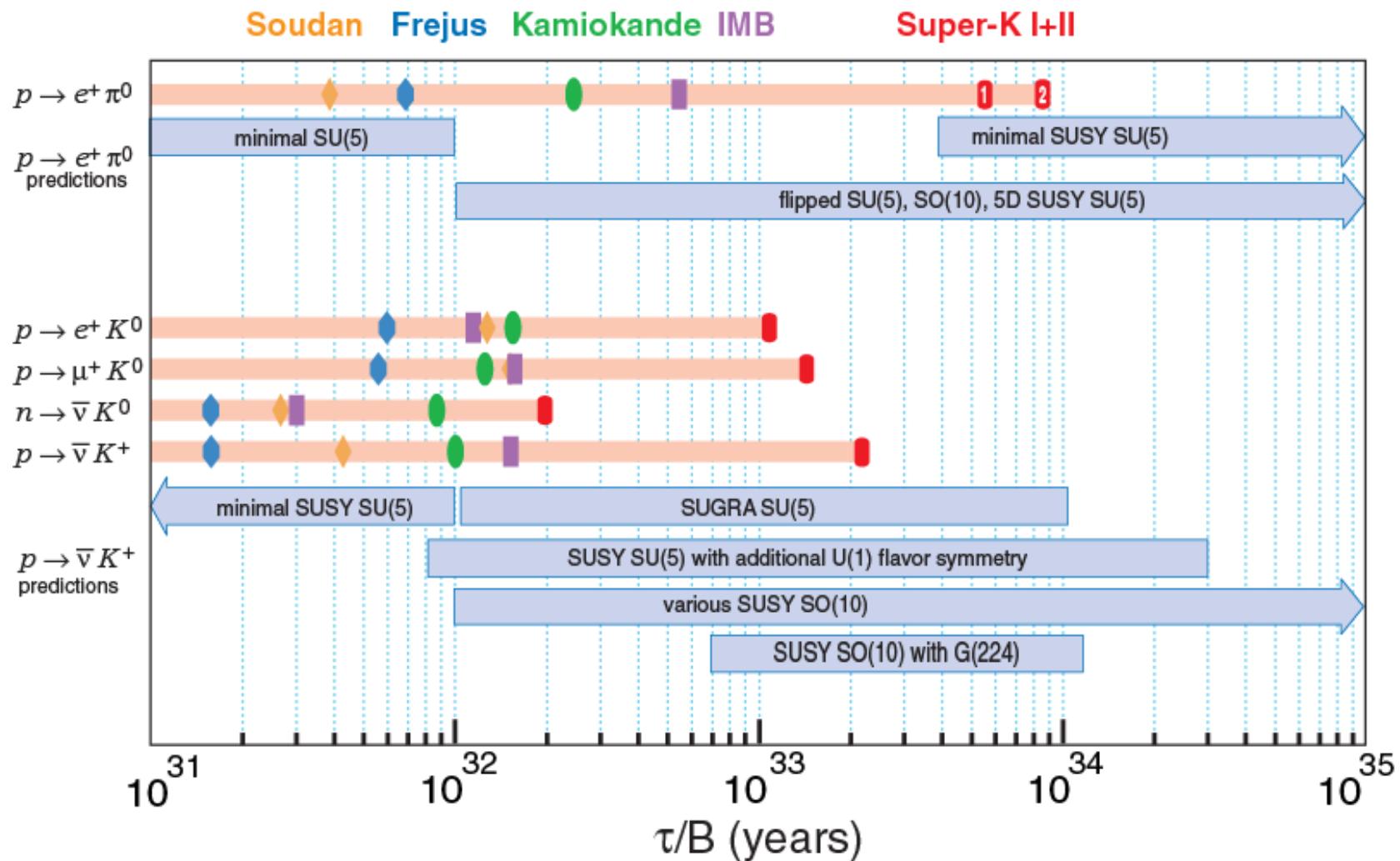
$$\tau/B > 8.4 \times 10^{33} \text{ years } \text{SK I + II}$$



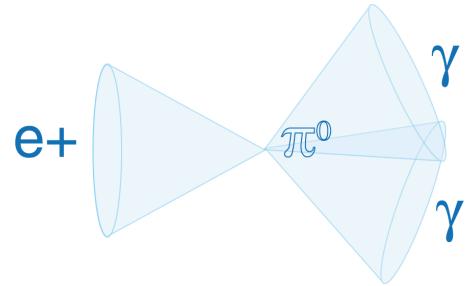
$$\tau/B = 10^{29-35} \text{ years SUSY}$$

$$\tau/B > 2.3 \times 10^{32} \text{ years SK I}$$

$\tau (e^+\pi^0) \Rightarrow 10^{36} \text{ years}$



Objective is to improve by at least 1 order of magnitude.
 Desirable to probe both $e^+\pi^0$ and $K^+\bar{v}$ (plus many many other modes)



$$p \rightarrow e^+ \pi^0 \quad (\text{or } \mu^+ \pi^0)$$

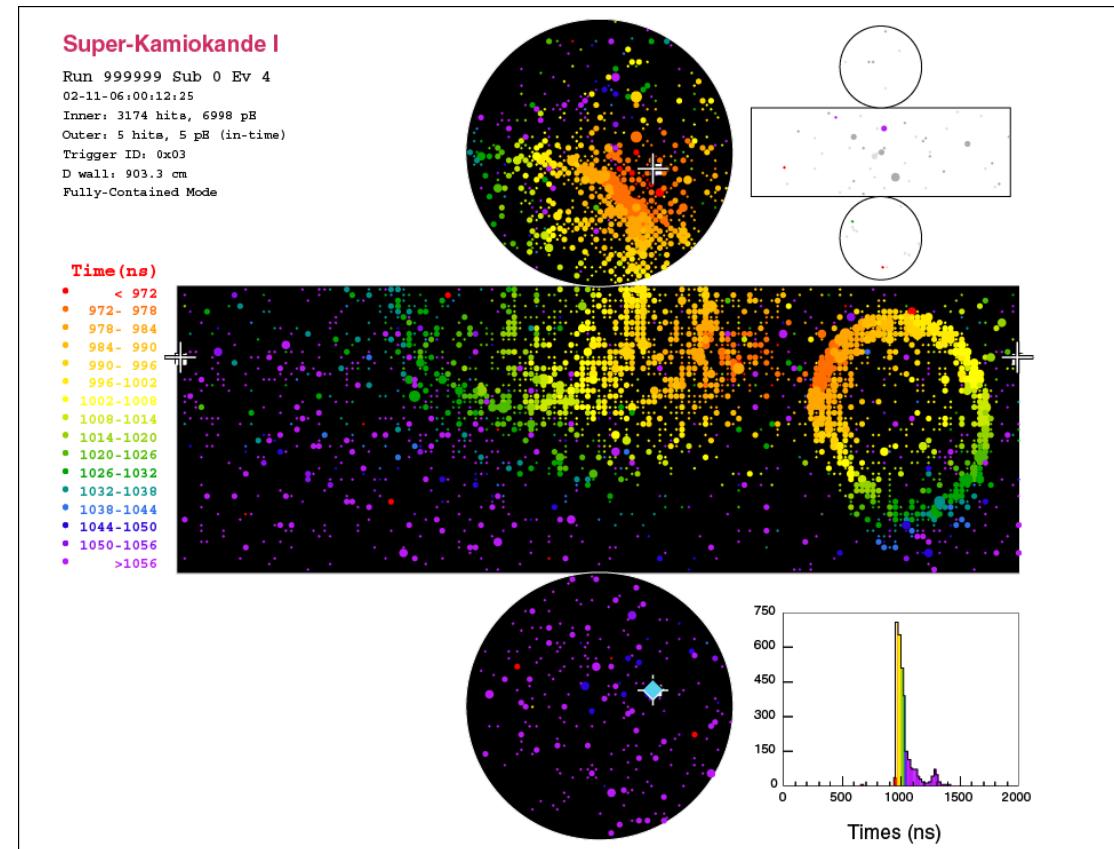
Event selection criteria:

- Fiducial volume
- Fully contained
- 2 or 3 rings
- All rings are e-like
- π^0 mass 85-185 MeV/c²
- No μ -decay electrons
- Mass range 800-1050 MeV/c²
- Net momentum < 250 MeV/c

For $\mu^+ \pi^0$:

- 1 μ -like ring
of correct momentum
- 1 decay electron

Example event: ($p \rightarrow \mu^+ \pi^0$)



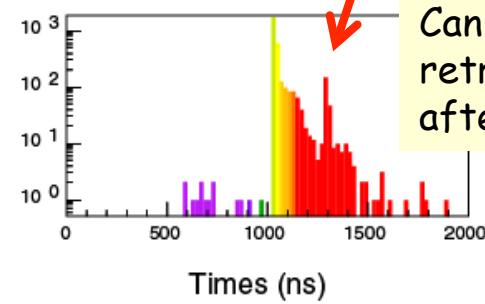
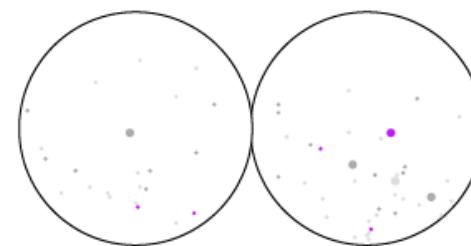
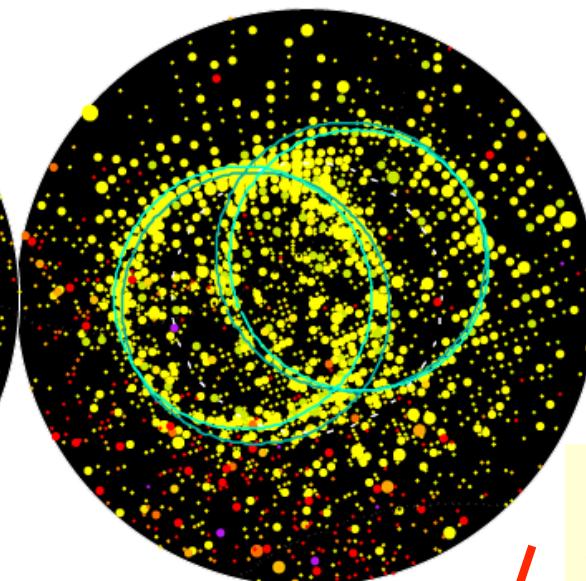
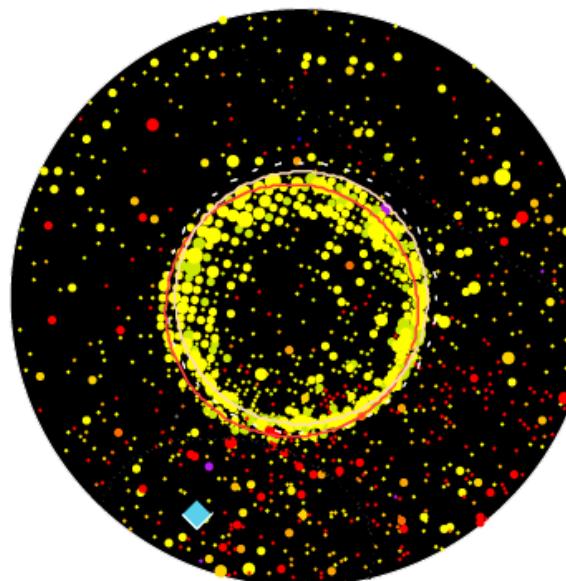
Sit at reconstructed vertex. Look forward/backward in two hemispheres

Super-Kamiokande I

Run 999999 Sub 0 Ev 4
02-11-06:00:12:25
Inner: 3174 hits, 6998 pE
Outer: 5 hits, 5 pE (in-time)
Trigger ID: 0x03
D wall: 903.3 cm
Fully-Contained Mode

Resid(ns)

- > 137
- 120- 137
- 102- 120
- 85- 102
- 68- 85
- 51- 68
- 34- 51
- 17- 34
- 0- 17
- -17- 0
- -34- -17
- -51- -34
- -68- -51
- -85- -68
- -102- -85
- <-102



Muon decay electron:
"same gate" type.
Can also retrigger detector after 1 ms

Proton Decay Signal MC

- Effective mass in ^{16}O
- Fermi motion
- Initial position (Woods-Saxon)
- Nuclear de-excitation γ
- Nuclear interactions
 - Elastic Scattering
 - Charge Exchange
 - Absorption

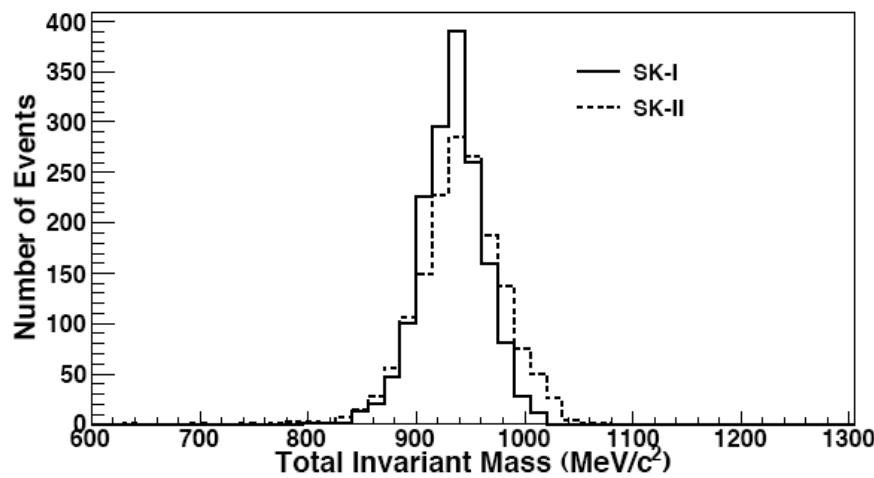
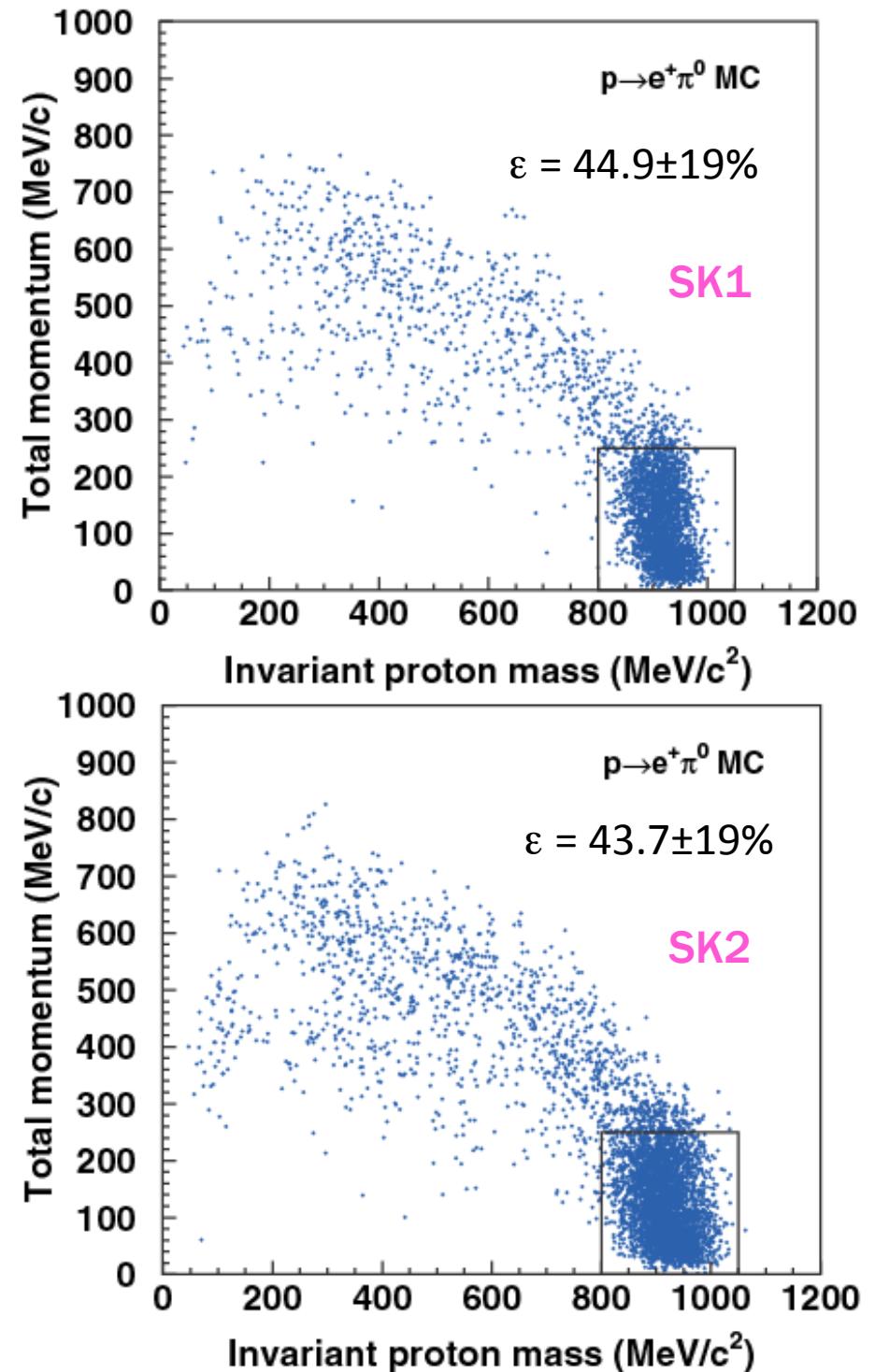
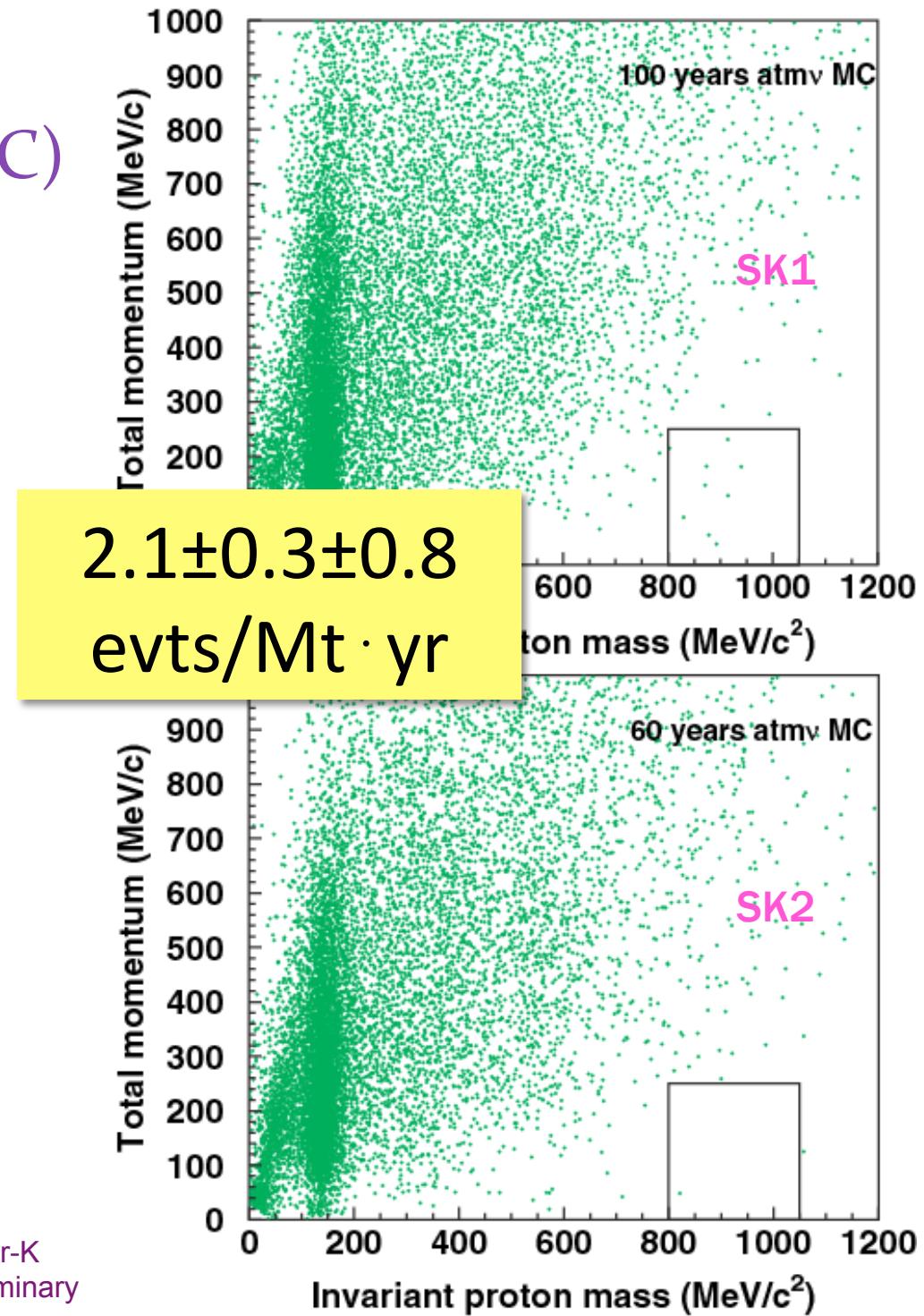
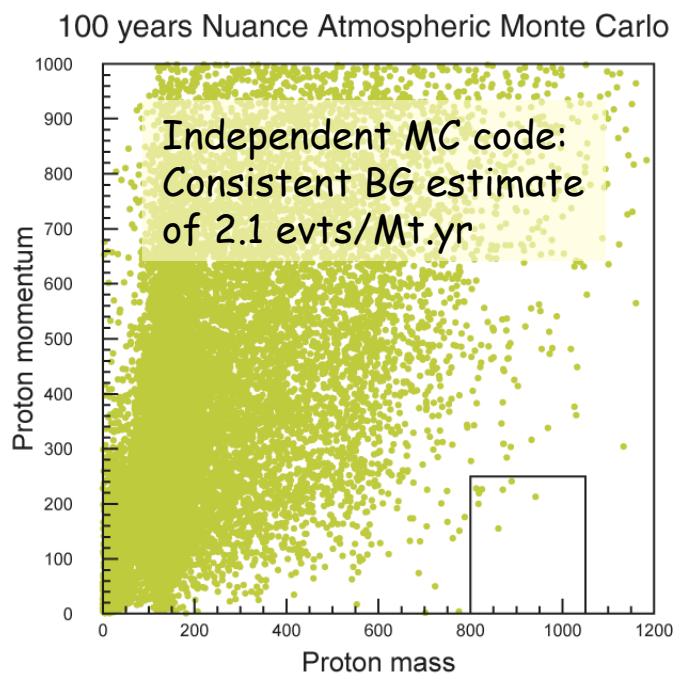


FIG. 1: Reconstructed proton mass for free proton decays of $p \rightarrow e^+\pi^0$ for SK-I (solid) and SK-II (dashed). The mean of reconstructed masses agree within 1%. The reconstruction resolution is 28.7 (RMS) MeV/c^2 for SK-I and 38.4 (RMS) MeV/c^2 for SK-II, respectively.

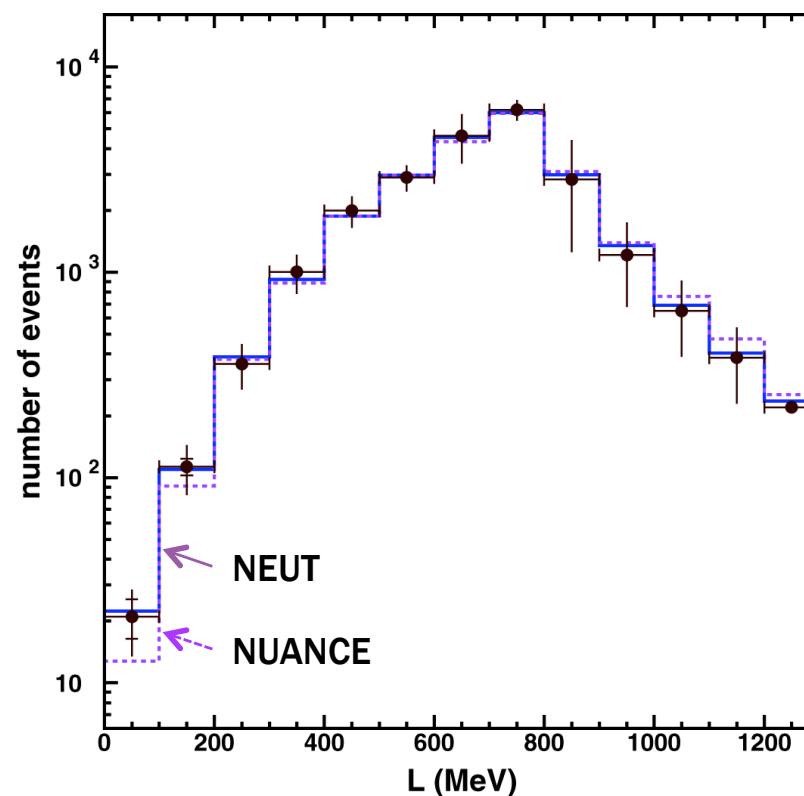
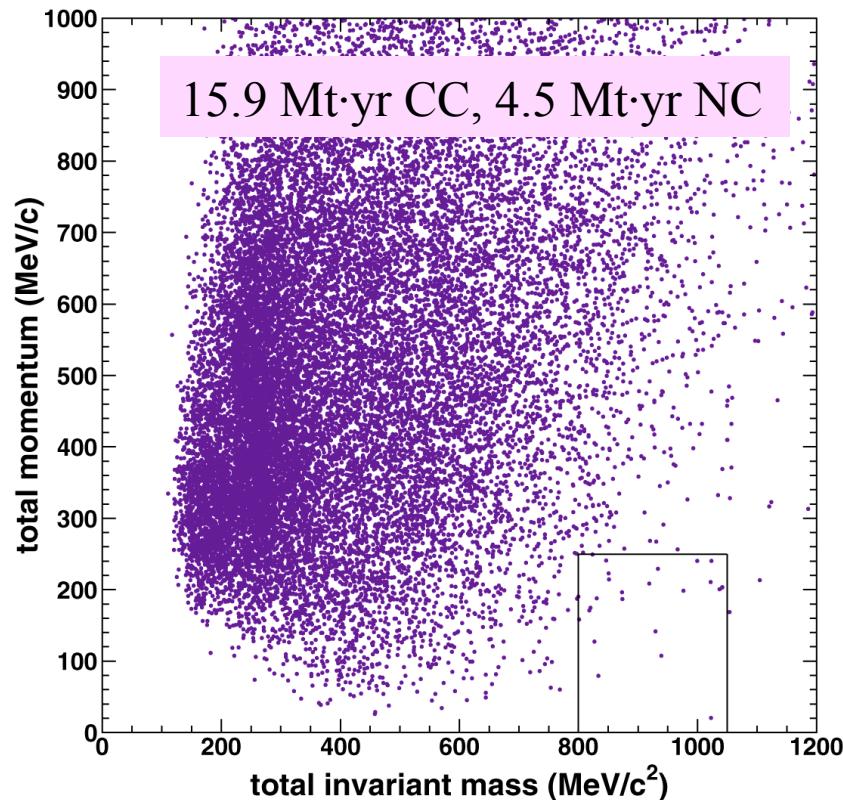
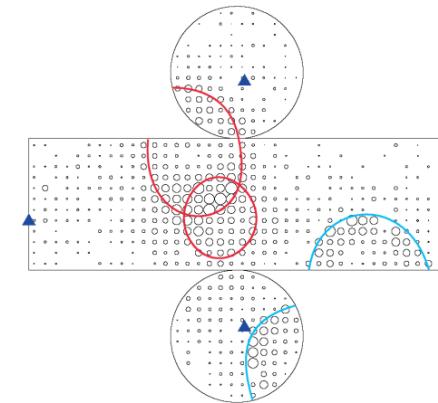


Atmospheric Neutrino Background Prediction (MC)

- Flux (E, flavor)
- Cross sections:
 - quasielastic
 - $1-\pi$, multi- π
 - DIS
- Pauli blocking
- Intranuclear scattering
- ν oscillations

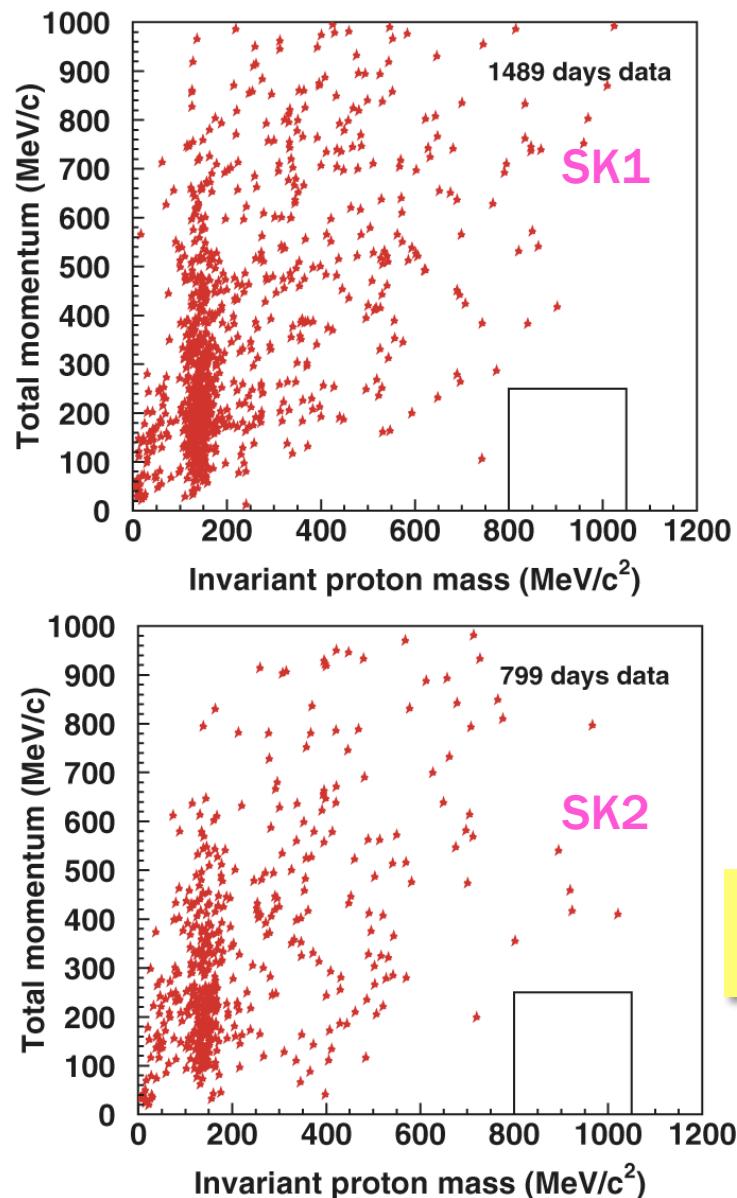


Direct measurement of proton decay background using K2K beam (1KT near detector)



$$e^+ \pi^0 \text{ BG} = 1.63^{+0.42}_{-0.33} (\text{stat})^{+0.45}_{-0.51} (\text{sys.}) \text{ evts/Mt} \cdot \text{yr}$$

$p \rightarrow e^+ \pi^0$ Search Results

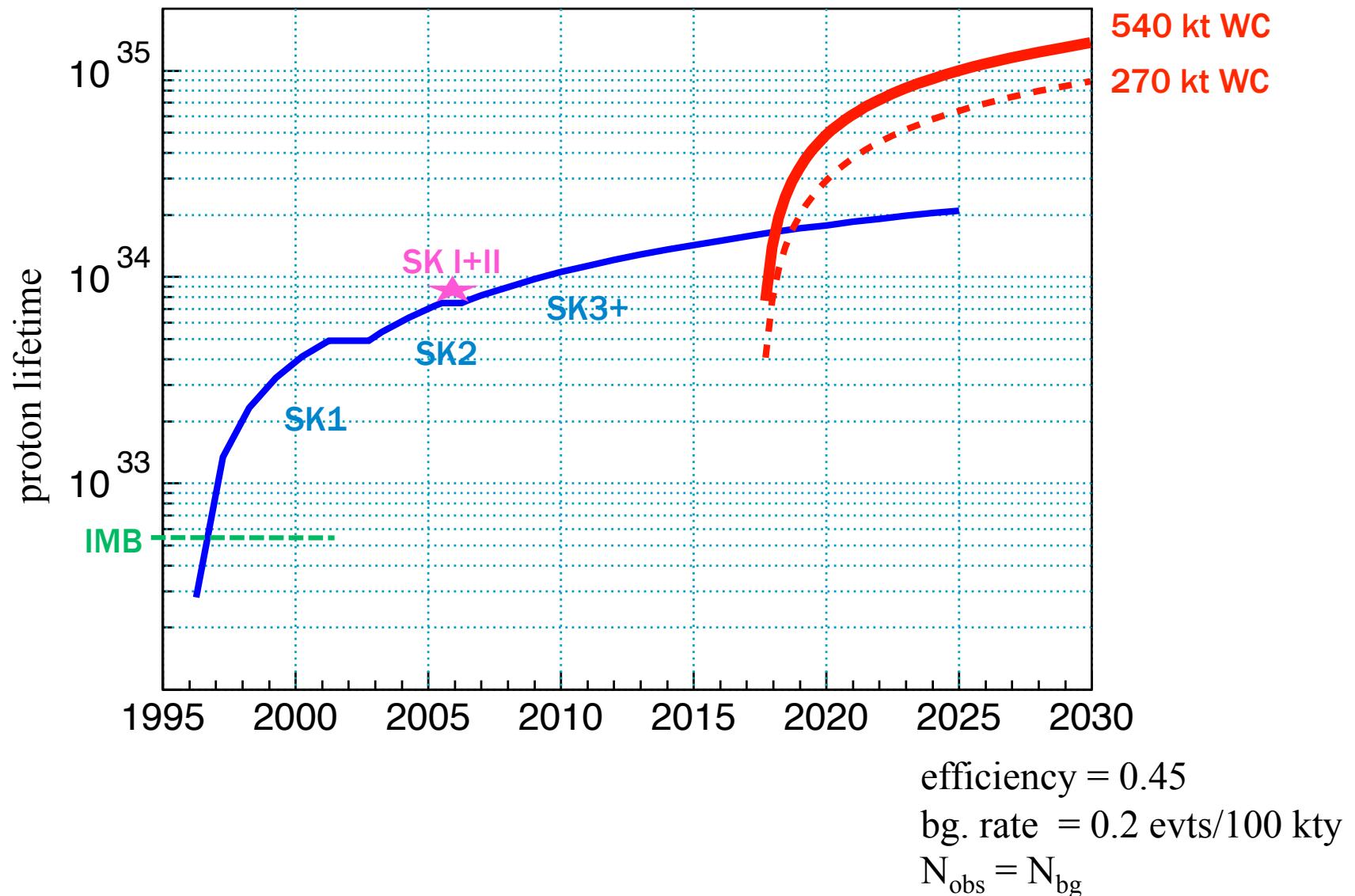


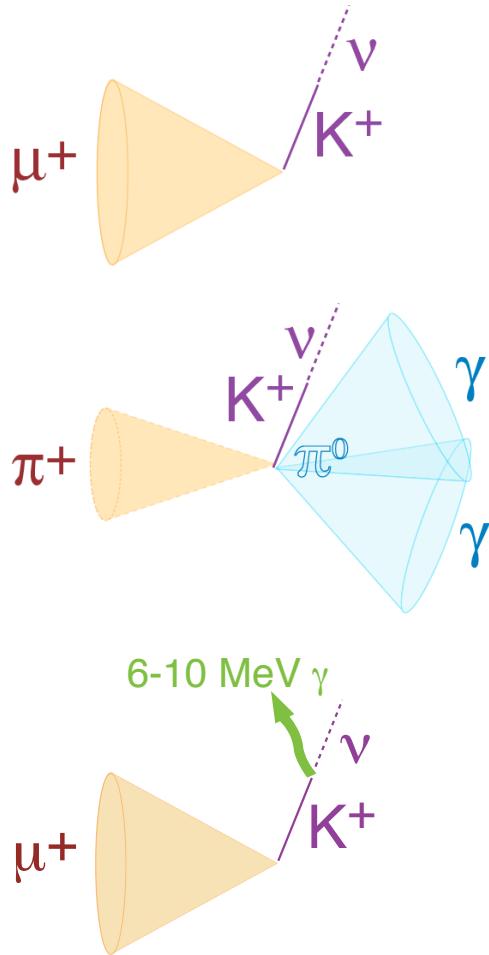
	SK-I	SK-II
Detection efficiency	$44.9 \pm 19\%$	$43.7 \pm 19\%$
Background estimate	$0.30 \pm 0.04 \pm 0.11$ events	
Exposure	1489.2 d (91.6 kt·yr)	798.6 d (49.1 kt·yr)
Data	0	0
Lifetime limit (90% CL)	5.5×10^{33} yr	2.9×10^{33} yr

$\tau/\text{BR} > 8.2 \times 10^{33} \text{ yr (90\% CL)}$

Super-K Preliminary

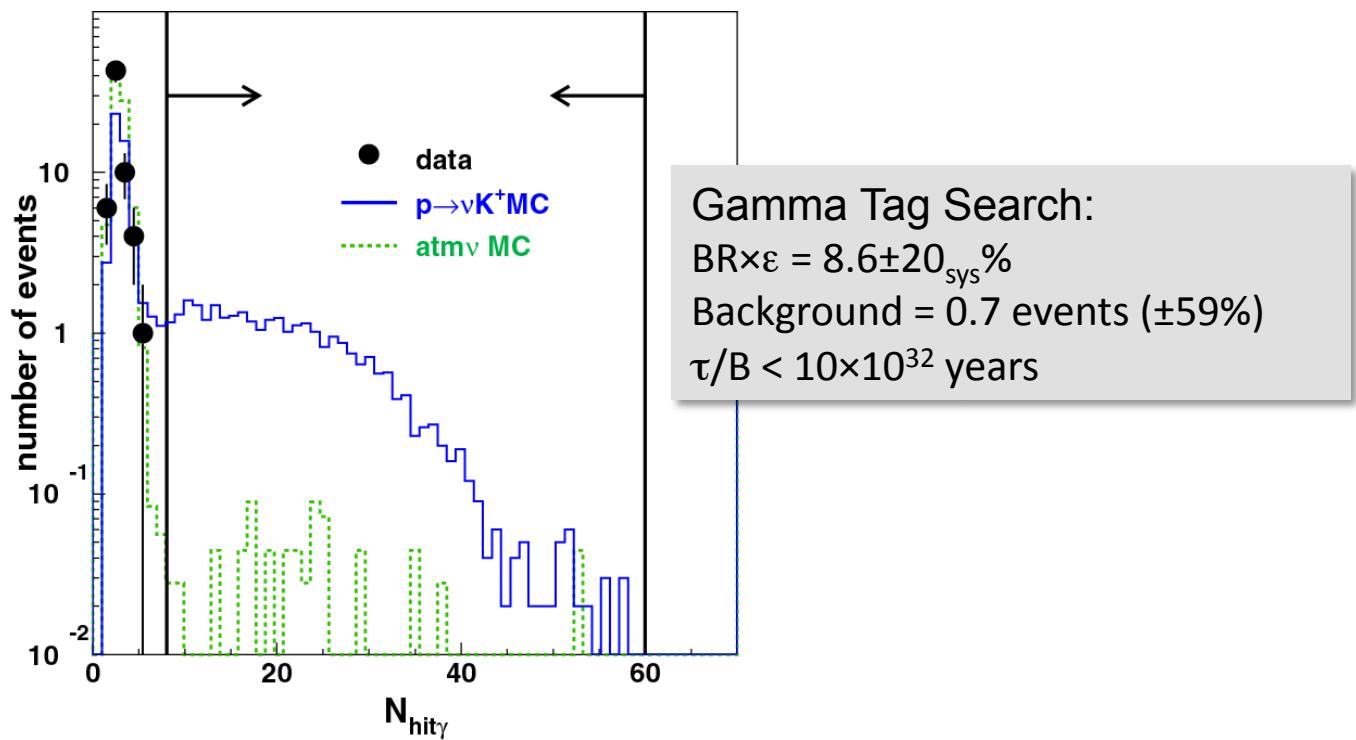
$$p \rightarrow e^+ \pi^0$$





Super-Kamiokande Search for ($p \rightarrow K^+ \nu$)

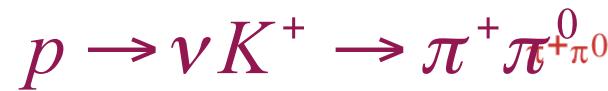
- ★ K^+ below Cherenkov threshold
- ★ Essentially a search for K^+ decay at rest
- ★ Three searches (eventually combined)
 - Monochromatic muon (65% BR, large background)
 - $K^+ \rightarrow \pi^+\pi^0$ (21% BR)
 - $K^+ \rightarrow \mu^+ \nu$ with early gamma tag from $^{16}O^*$



Super-Kamiokande

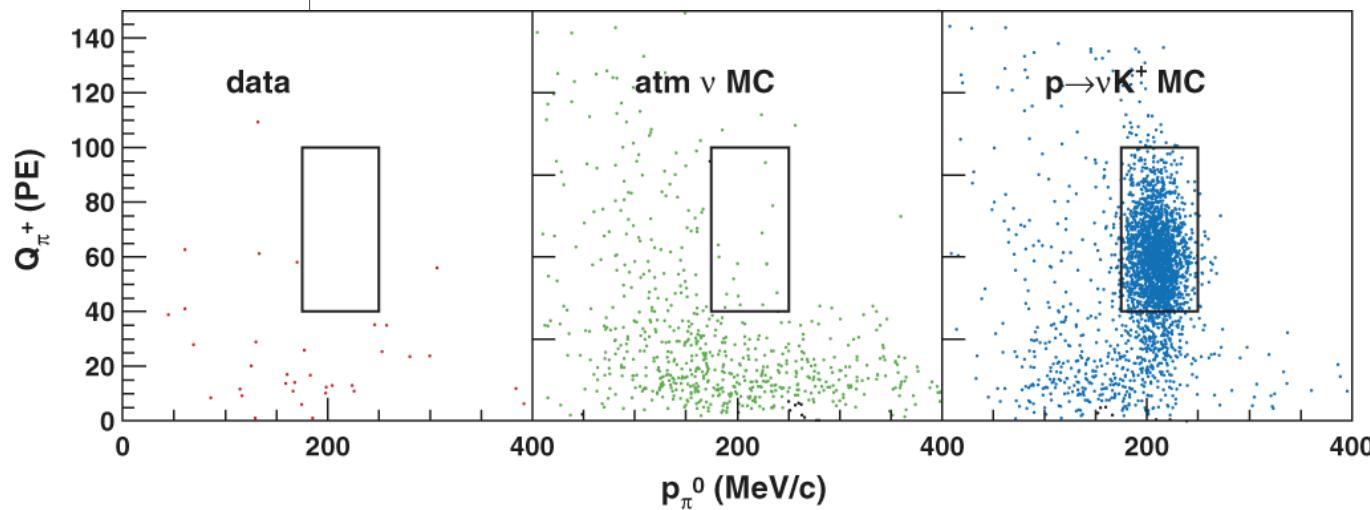
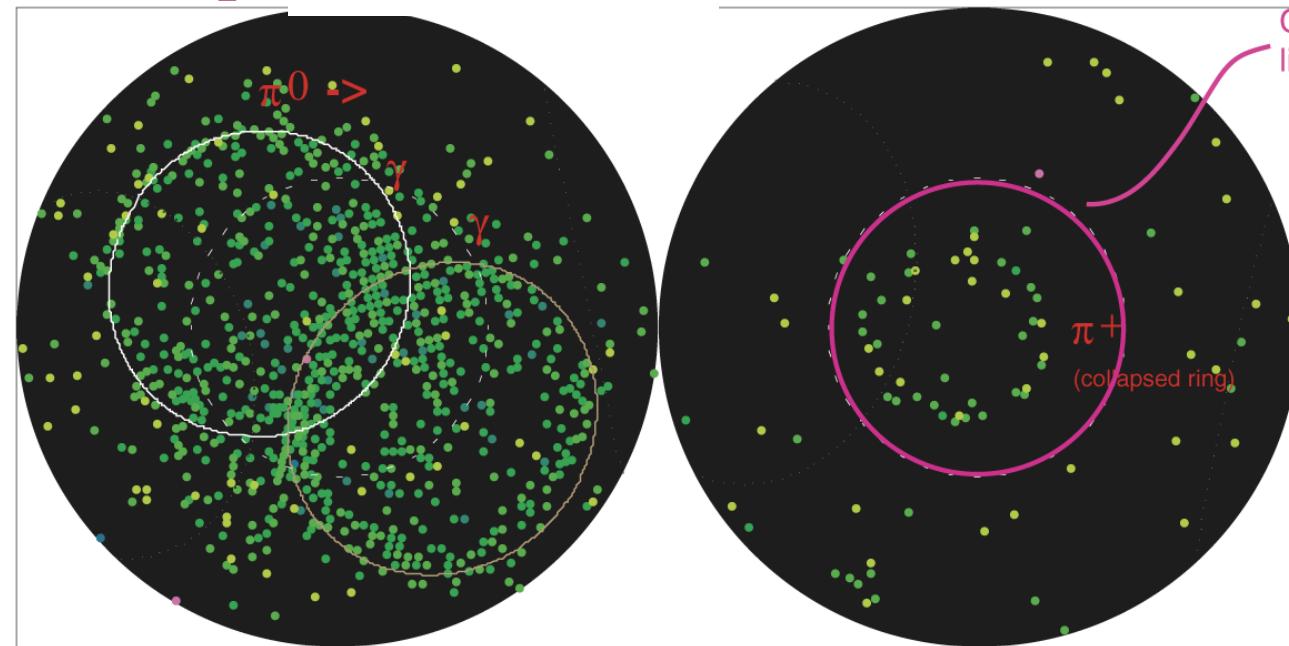
Run 1000000 Event 474
 1997-06-25T12:59:29
 Time to prev. event: 0.0us
 Inner: 1395 hits, 2128 pE
 Outer: 16 hits, 9 pE (in-time)
 Trigger ID: 0x03

Forward-backward hemisphere view of Monte Carlo event

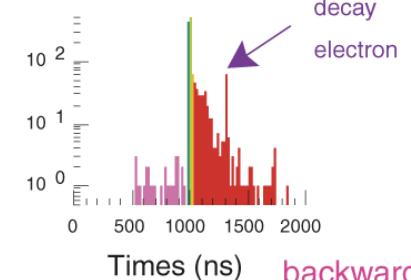


Resid(ns)

- > 45
- 40- 45
- 34- 40
- 28- 34
- 22- 28
- 17- 22
- 11- 17
- 5- 11
- 0- 5
- -5- 0
- -11- -5
- -17- -11
- -22- -17
- -28- -22
- -34- -28
- < -34

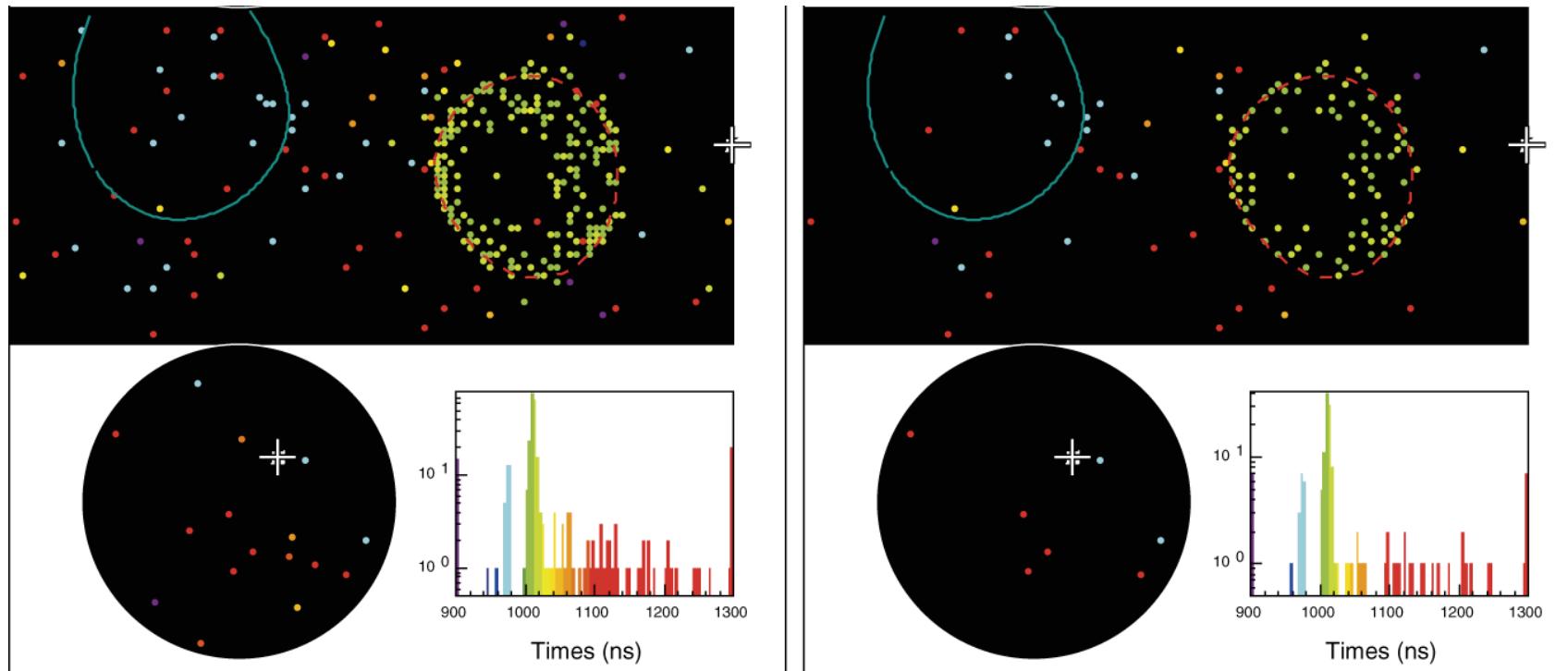


)
 pi⁺pi⁰ Search:
 $\text{BR} \times \varepsilon = 6.0 \pm 8.8_{\text{sys}} \%$
 $\text{BG} = 0.6 \text{ events } (\pm 74\%)$
 $\tau/B < 7.8 \times 10^{32} \text{ years}$



Re-optimization for SK-II	SK-I	SK-II
$N_{\text{hit}} \gamma$ (prompt gamma)	7-60 hits	5-30 hits
Backwards light ($\pi^+ \pi^0$)	40-100 p.e.	20-50 p.e.
Plus a few other cuts such as light outside cone, proton rejection cuts		

SK-II: Efficiency ↓, background ↑, need more work !



40% or 20% Photon Coverage?

	Super-K I (40% coverage)	Super-K II (20% coverage)
Sub-GeV vertex resolution	26 cm (e-like) / 23 cm (μ -like)	30 cm (e-like) / 29 cm (μ -like)
Sub-GeV particle mis-ID	0.81% (e-like) / 0.70% (μ -like)	0.69% (e-like) / 0.96% (μ -like)
Sub-GeV momentum resolution	4.8% (e-like) / 2.5% (μ -like)	6.3% (e-like) / 4.0% (μ -like)
$p \rightarrow e^+ \pi^0$ signal efficiency	$45.0 \pm 1.3 \pm 6.7\%$	$42.2 \pm 1.2 \pm 6.5\%$
$p \rightarrow e^+ \pi^0$ background	0.4 ($\pm 35\%$) events/100kty	0.04 ($\pm 35\%$) events/100kty
$p \rightarrow K^+ \nu, \gamma$ tag signal efficiency	$8.4 \pm 0.1 \pm 1.7\%$	$4.7 \pm 0.1 \pm 1.0\%$
$p \rightarrow K^+ \nu, \gamma$ tag background	0.72 ($\pm 28\%$) events/100kty	1.4 ($\pm 30\%$) events/100kty
$p \rightarrow K^+ \nu, \pi^+ \pi^0$ signal efficiency	$5.5 \pm 0.1 \pm 0.7\%$	$5.7 \pm 0.1 \pm 0.4\%$
$p \rightarrow K^+ \nu, \pi^+ \pi^0$ background	0.59($\pm 28\%$) events/100kty	1.0($\pm 30\%$) events/100kty
T2K CC ν_e likelihood effic.	83.7% (± 0.1 stat)	84.8 %
T2K BG likelihood effic.	21.3 %	21.5 %

Preliminary numbers, for comparison purposes.
Final published efficiencies and BG may differ.

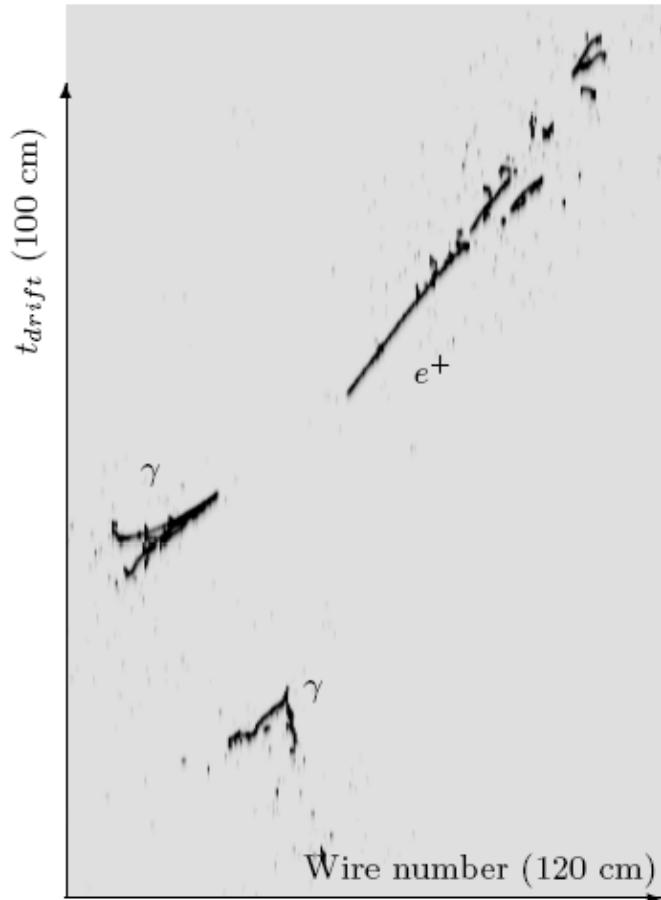


FIG. 14: Simulated $p \rightarrow e^+\pi^0$ event. The displayed area covers $120 \times 100 \text{ cm}^2$.

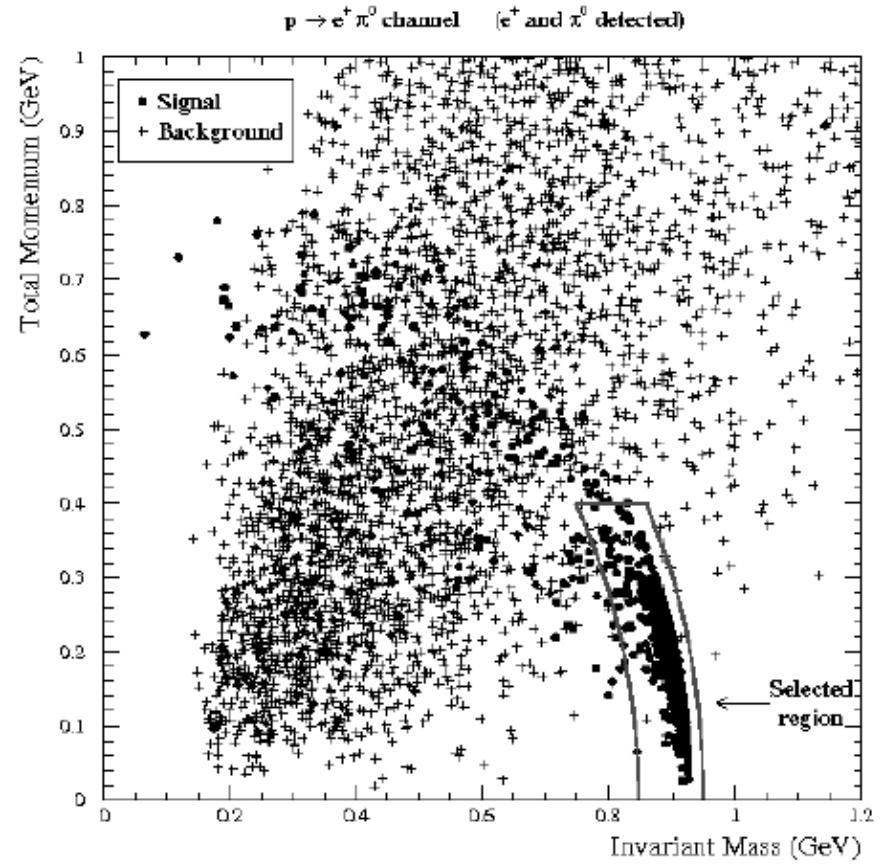
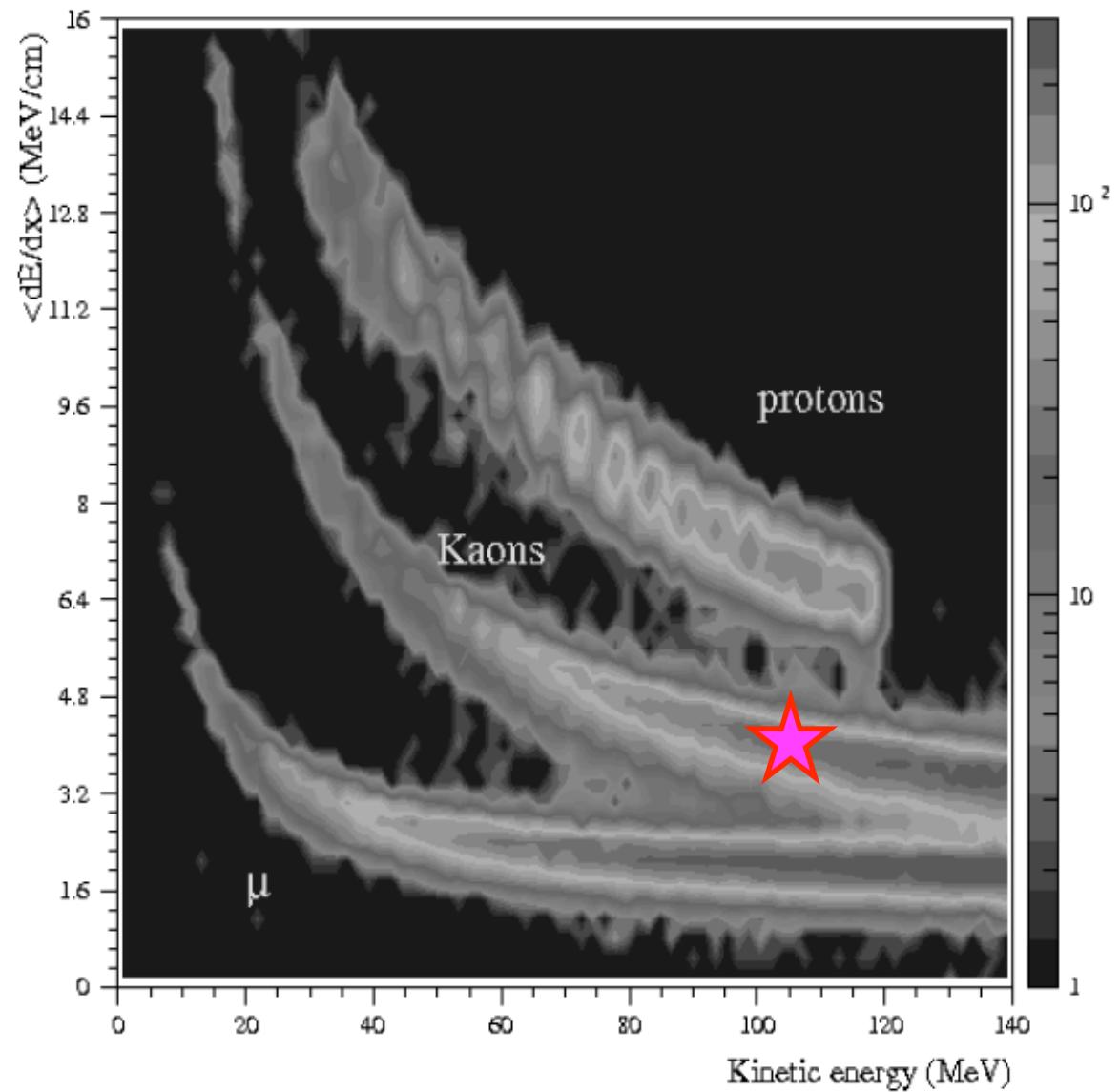
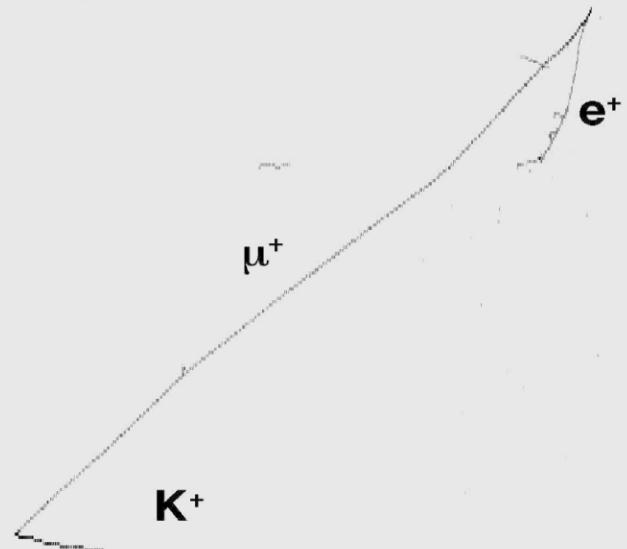


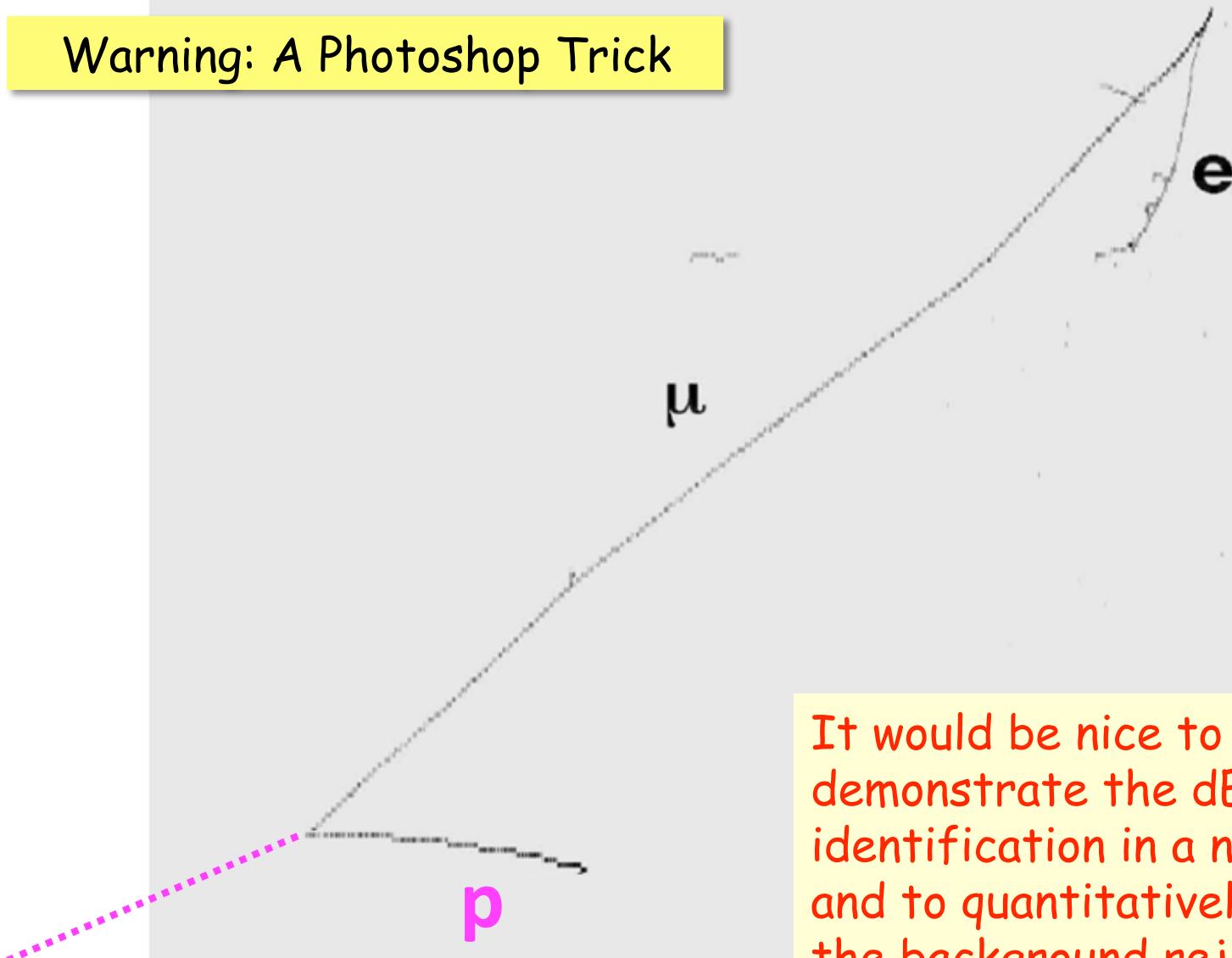
FIG. 16: Kinematic cut in the $p \rightarrow e^+\pi^0$ channel: in the plane defined by the invariant mass and the total momentum, crosses represent background and spots signal events. The band indicates the cut region ($0.86 \text{ GeV} < \text{Total Energy} < 0.95 \text{ GeV}$), i.e. all events inside the band are accepted.

$p \rightarrow \bar{\nu} K^+$



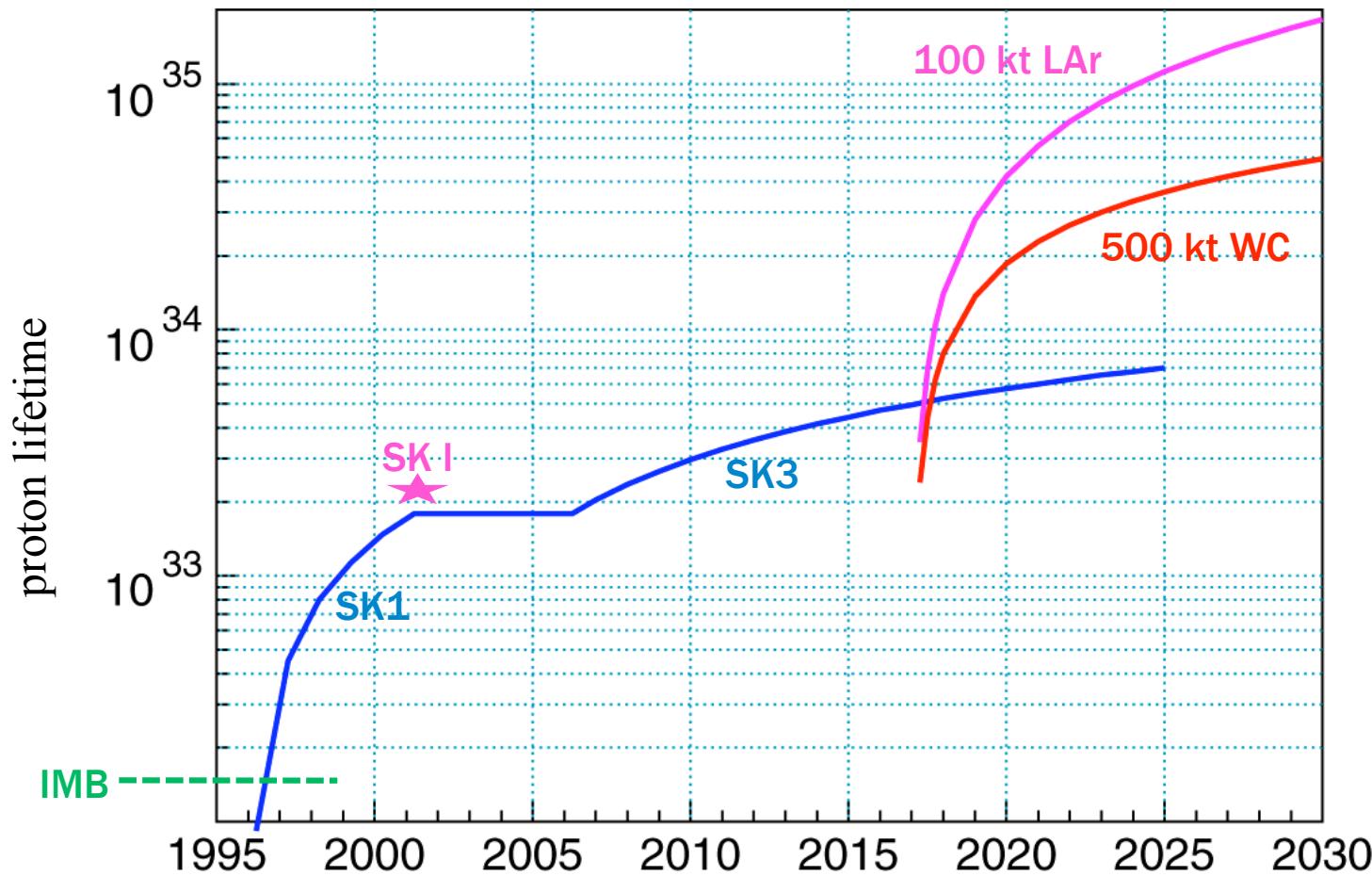
Cuts	(p3) $p \rightarrow K^+ \bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One kaon	96.8%	308	36	871	146	282	77
No other charged tracks, no π^0	96.8%	0	0	0	0	57	9
$E_{vis} < 0.8$ GeV	96.8%	0	0	0	0	1	0

Warning: A Photoshop Trick



It would be nice to systematically demonstrate the dE/dx identification in a neutrino beam, and to quantitatively establish the background rejection.

$$p \rightarrow K^+ \nu$$



Background: events/100 kt•yr

	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow e^+ \pi^0$	45%	0.2	45%	0.1
$p \rightarrow \mu^+ \pi^0$	36%	0.2	45%	0.8
$p \rightarrow K^+ \nu$	14%	1.3	97%	0.1
$p \rightarrow K^0 \mu^+$	8%	0.8	47%	0.2
n-nbar	10%	21		

No advantage for LAr over water for $e^+\pi^0$: efficiency dominated by nuclear absorption of the π^0 – for both.

Big advantage for LAr over water for $K^+ \nu$: K^+ is below Cherenkov threshold but can be identified by dE/dx in LAr TPC.

LAr should do well with n-nbar: spherical multipion final state.

Key Points

- ❖ Proton decay adds tremendous scientific merit to a large detector at DUSEL. DoE has historically considered proton decay a core objective. It is “non-accelerator” though, so it is not always high priority.
- ❖ There is merit in both LAr and WC detectors. If SUSY is seen at the LHC, pursuing LAr at 100kt is imperative. To complete the picture of Grand Unification, proton decay must be probed to 10^{36} years or better (not exactly what we are discussing today).
- ❖ More generally, significant improvement over projected SK limits drives a request for as much mass as possible.